Applications of microwave heating in mineral processing

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Many minerals are effective absorbers of microwave energy, whereas in general gangue materials are not. This suggests applying microwave heating to mineral processing to effect selective heating of mineral phases. Many mineral processing applications have been tested only on a laboratory scale; the engineering realities of large-scale operations have largely been overlooked. Of particular concern are the modest power outputs of industrial magnetrons relative to the power requirements in mineral processing operations, the high capital cost of microwave equipment and the poor penetration depth of microwaves. Review of these applications, and comparison with guidelines developed for successful microwave technology transfer, suggests that niche areas for microwave heating are in the processing of low-throughput concentrates, especially where volumetric heating leads to enhanced rates of energy transfer. The use of combined heating sources should be investigated.

Principles of microwave heating

Electromagnetic radiation at the ISM (industrial, scientific and medical) frequencies [915 (896 in the U.K.) and 2450 MHz] interacts with dielectric materials to achieve volumetric heating, offering advantages over conventional heating. The dominant heating mechanism is the dipolar re-orientation loss mechanism; permanent or induced dipoles in the dielectric are unable to follow the rapid reversals in the applied electromagnetic field. As a result of phase lag, power is dissipated in the material.

The complex dielectric constant of a material (generally a function of temperature, moisture content, density and electric field direction)

$$\varepsilon^* = \varepsilon' - j\varepsilon_e'' \qquad (1)$$

accounts for dipolar re-orientation and other loss (heating) mechanisms. Von Hippel[1] is a good source of data.

If $\varepsilon_e'' < 10^{-2}$, the material is generally not a good candidate for microwave heating. For $\varepsilon_e'' > 5$, the power penetration depth (D_p) could be quite small (of the order of several centimetres). For objects larger than this it is likely that highly non-uniform heating would result. D_p is defined as the depth at which the incident power drops to $1/e$ of its value at the surface:

$$D_p = \frac{\lambda}{2\pi\sqrt{2\varepsilon'}}\left[(1+(\varepsilon''/\varepsilon')^2)^{1/2} - 1\right]^{1/2} \qquad (2)$$

where λ is the free space wavelength of incident radiation. D_p increases with decreasing frequency. It is vital to have accurate data available to design microwave heating processes. It is also important to have dielectric properties appropriate to the form of the material to be heated. Bulk metals, for instance, reflect microwaves, whereas finely divided metal powders absorb quite well.

The principal components of a microwave heating system are the power supply and microwave generator, the applicator and the control circuitry. The most common microwave source is the magnetron, available in powers up to 70 kW at 915 MHz. Microwave applicators are metallic enclosures that contain the material to be heated. Travelling wave applicators are suitable for thin sheets of material. Single mode cavities are useful for processing small quantities of material and are easily designed. The most versatile applicator is the multimode cavity. This is typically a large box with dimensions greater than the free space wavelength of the radiation. Specialized design features (e.g. mode stirrers and slotted waveguide feeds) are usually required to overcome inherent non-uniform heating in this type of cavity. It is possible to design cavities to process material continuously and to allow insertion of measurement devices, while retaining the microwave integrity to ensure a radiation flux less than 5–10 mW cm^{-2} at a distance of 50 mm from the equipment. Control circuitry usually allows temperature regulation by power manipulation, and sometimes automatic impedance matching. Specialist microwave engineering is required for equipment selection and applicator design. Combining microwave heating with other energy sources may offer more efficient heating than microwaves alone.[2]

Scale-up and technology transfer

Growth of industrial microwave heating is slow. Worldwide sales of industrial microwave equipment were estimated at only US$50 million in 1994.[3] In 1996, there were estimated to be about 600 microwave installations with a total installed power of 100 MW in the U.S. Of these, 90 % were for bacon cooking, rubber preheating or meat tempering. Reluctance to abandon existing technologies and uncompetitive economics are commonly cited as reasons for slow growth of the industrial sector. Table 1 indicates factors likely to lead to commercialization of microwave heating applications.[4]

Scale-up guidelines have also been compiled; this is important as most research work is still carried out in the laboratory, and often little consideration is given to applying the technology on a commercial scale (see Table2).

Applications of microwave heating in minerals processing

Early research into microwave heating of minerals involved establishing heating rates.[5,6] The observation that many minerals coupled well with microwaves while gangue materials did not, suggesthat one of the benefits of microwave heating in mineral processing is selective heating of valuable mineral phases. Subsequently, research broadened and applications ranging from coal cleaning[7] to treatment of refractory gold ores[8] have been examined. A comprehensive review of many of these applications is available.[9] In spite of this effort, there remains the belief in the mineral processing industry that the engineering realities of these applications have been neglected. In the following section the realities of a selection of mineral processing applications are examined.

Microwave treatment of refractory gold concentrates

Haque[8] irradiated refractory gold concentrate mixed with NaOH; sulphides were removed by water washing and 99 % extraction of the gold was achieved after leaching. Specific energy consumptions of approximately 3 kWh kg^{-1} were used. EMR (Canada) has a 2 t day^{-1} pilot plant treating refractory gold ore in an

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Table 1. Factors leading to commercialization of microwave heating applications.

Factors likely to lead to successful commercialization	Factors likely to lead to failure
Compelling advantage to use of microwaves	Competition from existing technology
Solving a real industrial problem, as opposed to force-fitting the technology	Trying general-purpose equipment (e.g. the domestic oven), especially that not designed for heat transfer
Using combined energy sources, especially when heating above 200°C. Bulk heating with conventional energy sources, trimming with microwaves	Lack of support for the technology (after-sales service etc.), poor understanding of the technology (unrealistic expectations)
Good pilot work, examples of success	Basing applications in energy savings alone (plug-to-product efficiency 50–70 %)
Interdisciplinary approaches, using applications specialists, microwave engineers and heating and control specialists	High capital cost (US$1000 – 7000 kW^{-1} installed), giving a total annualized cost (operating and capital) of about $0.08 kWh^{-1}
Timeliness	Reluctance to be first
Compatibility with existing process and retrofitting	Need for custom design for each application
High-value product	Low value product (<US$2 kg^{-1})

Table 2. Scale-up guidelines for microwave heating.

Scale-up consideration	Comments
What type of applicator will be used?	Laboratory applicators will seldom be appropriate for large throughputs. How will penetration depth problems be overcome?
What frequency will be used?	915 MHz is the preferred industrial frequency (higher powers, more efficient, greater penetration depth). Most laboratory work is done at 2.45 GHz. Use a model to scale effect if there is no 915 MHz equipment available. Loss factor varies with frequency
Do not scale power more than 10 times	
Use a system design approach	
Equipment design is not linear	
Think production in the laboratory	Circulators will not be available to cope with reflected power, the operating environment is likely to be dirty

oxygen-limited environment using a microwave fluidized bed. The company claims almost complete gold recovery by microwave heating to 350–400 °C, followed by leaching. The energy consumption is claimed to be only 13.9 kWh t^{-1}, although this seems very low. Projecting to a 200 t day^{-1} plant they predict an operating cost of about $8 t^{-1} and capital expenditure of $200 000 for the microwave unit. It is believed that EMR is proceeding with a full-scale unit.

Microwave regeneration of granular activated carbon

A pilot plant to regenerate 12 kg h^{-1} activated carbon by microwave heating at Barrick's Holt-McDermott gold mine in Ontario, Canada, has been reported.[10] A hot air pre-dryer followed by a vertical microwave regeneration unit operating at 915 MHz was used. Carbon losses were reduced by half compared to a rotary kiln. Although the capital cost of the microwave equipment is higher than for the rotary kiln, the predicted operating costs for a 120 kg h^{-1} unit were one-third of a conventional system. A payback time of 15 months was predicted.

Bradshaw *et al.*[11] regenerated spent granular activated carbon by microwaves at 2450 MHz in a multimode cavity. Optimum regeneration conditions were 600 °C with no hold at set point with a steam flow rate of 0.18 kg h^{-1}. In general, microwave regenerated material outperformed conventionally regenerated carbon. The preliminary capital cost estimate for a 100 kW microwave unit to process 120 kg h^{-1} was US$135 300; a Minfurn costs $120 500 and a rotary kiln $118 900. Operating costs for the three systems per ton of carbon were $66, $70 and $88, respectively.

Although these results seem promising, commercialization in South Africa appears remote. Carbon research receives low priority, while the electrically heated rotary kiln is an established technology that will not easily be replaced. Competition will come from direct, resistively-heated furnaces, such as the Minfurn and a newly-developed direct, resistively-heated rotary kiln. The latter should eliminate problems of preferred current paths in the Minfurn (with non-uniform regeneration) and will be more efficient than either the microwave unit or the conventional rotary kiln. It seems likely that unless it can be shown clearly that carbon properties are better with microwave regeneration, as was done by Strack *et al.*,[10] microwave technology is unlikely to supercede this application.

Thermal stress generation through microwave heating of concentrates

Salsman *et al.*[12] made a theoretical analysis of thermal stresses developed in a 250-μm sphere of pyrite and calcite (pyrite core) when subjected to short pulses of microwave energy. High power densities ($\sim10^{14}$ W m^{-3}) for short times (40 μs) generated thermal stresses at the calcite/pyrite interface that would probably be sufficient to rupture the material. Continuous heating did not work in this application, as the heat generated selectively in the pyrite cores had time to diffuse into the calcite host, thus not providing steep enough thermal gradients. An energy requirement of 0.8 kWh t^{-1} of a sulphide ore was predicted.

This could be implemented in two ways. Continuous power could be used (which would require an 8-kW unit for a modest throughput of 10 t h^{-1}), with the concentrate exposed to the appropriate power density (1.455×10^{13} W m^{-3}) for 40 μs. If this could be achieved it would mean that standard microwave equipment could be used and that the cost would be reasonable. However, to achieve the short residence times and high power densities, the microwave cavity would have to be extremely small (4×10^{-8} m^3), which is clearly impractical.

The alternative is to use pulsed microwave equipment, as used for radar, and in extremely high powers for linear accelerators (6 GW with pulses of 5 μs and cycle times of 5 ms). The trade-off here is one of power requirement *versus* a reasonable cavity size. Two cases illustrate the point. Pulsing for 40 μs every 5 ms requires a microwave supply rated at about 1 MW. A cylindrical TM_{01} cavity would be appropriate. Utilizing 10 mm of the diameter for heating requires a 65-mm-high cavity through which the linear velocity is about 13 m s^{-1}. Pulsing every 5 s requires a cavity volume 1000 times larger, but with more manageable velocities. However, the pulse power requirement would be 1 GW. The power supply for such a unit becomes colossal, and it is expected that the equipment cost would then be very high.

A possible application of the technology could be in bioleaching of copper from chalcopyrite. In this process, ultra-fine grinding of the concentrate from 100–200 μm to 90 % –10 μm is required, with a specific energy requirement of about 100 kWh t^{-1}. A cheaper route to eliminate this step would reduce costs. Another application is separating rutile/zirconia from a strongly bonded quartz shell. While the prospect is attractive, it is apparent that there are serious engineering problems that would have to be overcome. The costs involved in doing this have to be weighed against the downstream processing benefits.

Microwave reduction of iron ore

In the conventional direct-reduction process, it is difficult to get the heat to the centre of the iron ore pellets fast enough to supply the heat required by the endothermic Boudouard reaction, and 'cold centres' result. Microwave heating, which is volumetric, can overcome this problem. There is also the added benefit that reduction of Fe_3O_4 to FeO, which is endothermic, involves heating an excellent microwave absorber (Fe_3O_4). Microwave reduction of hematite and magnetite with carbon has been investigated.[13,14] Encouraging results were obtained by heating 50 g of ore containing about 60 % Fe, plus reductants, for 10 min using 1400 W of microwave power. The specific energy consumption, 7.8 MWh t^{-1} Fe, can be compared with a typical electrical energy requirement for a conventional direct-reduction plant of 0.07 MWh t^{-1}. The laboratory experiments have therefore been performed at very high specific energy inputs. There would clearly have to be a significant benefit of using microwaves to justify this high energy consumption. If it were possible to achieve satisfactory results using 0.07 MWh t^{-1}, a 200 000 t yr^{-1} plant would still require a 1.7-MW microwave system. This is bigger than any existing microwave plant by a factor of about 3. Applicator design to handle such large throughputs, while overcoming penetration depth problems, remains an unknown area. A profitable area of investigation seems to be the use of combined heating for this application.

Microwave treatment of ilmenite

Oxidation of ilmenite (TiO_2), followed by reduction at 800 °C, enhances the chemical activity of the mineral. Iron can then be extracted preferentially to yield a titanium-rich beneficiate for the production of TiO_2. Microwave heating was compared with conventional heating in a muffle furnace.[15] The required reduction temperature was quickly reached with microwaves but the period of heating needed to be extended to allow time for diffusion of reductant and gaseous products. This suggested using microwaves to effect rapid heating while using a cheaper energy source to maintain temperature. Iron extraction efficiency of the best microwave sample was not as good as the best conventionally heated sample; however, conventional reduction required 4–8 hours as opposed to 10 min using microwaves. The specific energy consumption for reduction using microwaves was 1.9 kWh kg^{-1} TiO_2.

Concluding remarks

The mineral processing industry is justly cautious about adopting microwave technology. The problems of treating large throughputs, overcoming penetration depth problems and the true economics of microwave technology are often overlooked in the laboratory. These aspects all dictate that treating lower tonnage, higher value concentrates would be preferred. Few laboratory investigations consider combined heat sources, although it is recognized that this is often essential for high-temperature commercial applications. There is considerable resistance to retrofitting in the industry. This is unfortunate, because often it has been found that retrofitting microwave heating is economically advantageous.

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